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MIDWEST STRUCTURAL SCIENCES CENTER: 2006–2007 ANNUAL REPORT

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University of Illinois at Urbana-Champaign

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Interim Report

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14. ABSTRACT
The Midwest Structural Sciences Center (MSSC) is a collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/VA SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames in a risk-quantified design process. The MSSC is conducting research on aerothermostructures with a five to ten year horizon in four key areas: coupled thermo-mechanicalacoustic analysis and simulation, identification and definition of structural limit states, risk-quantified structural assessment, and experimental capabilities for validation of structural models.

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The Midwest Structural Sciences Center is a collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/VA SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames in a risk-quantified design process.

The University of Illinois Midwest Structural Sciences Center (MSSC) was established in February 2006 to rapidly expand the technical manpower available to the Structural Sciences Center at AFRL/VA SSC. The MSSC has the long-term objective of developing the knowledge base required for validated, risk-based tools for the design and simulation of spatially-tailored aero-thermo structures (STATS). In close collaboration with the scientific and engineering staff of AFRL/VA SSC, faculty, staff and students from the University of Illinois and its partners will complete medium-term research projects (five- to ten-year horizons) in four key areas:

- Coupled thermo-mechanical-acoustic analysis and simulation of spatially-tailored aero-thermo structures
- Identification and definition of structural limit states for spatially-tailored aero-thermo structures
- Computational frameworks and methodologies for risk-quantified structural assessment of spatially-tailored aero-thermo structures
- Experimentation, verification, and validation

MSSC Technical Program Features

Risk analysis and quantification
Multiscale materials modeling
Generalized FEM for acoustic modeling
Sensitivity analysis
Experimental validation

MSSC Partners

Air Force Research Laboratory Air Vehicles Directorate, Structural Sciences Center
University of Illinois at Urbana-Champaign
Aerospace Engineering
Civil and Environmental Engineering
Computational Science and Engineering
Mechanical Science and Engineering

The team employs analytical, computational, experimental, personnel and financial resources from several university departments and AFRL organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are being applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their colleagues at AFRL/VA SSC to evaluate and extend the understanding of materials and structures in aerospace structural components that experience extreme combined environments.

1 Introduction

1.1 Air Force Structural Sciences Mission

Future missions of the Air Force, such as prompt global strike and operationally responsive space access, will be performed with air/space vehicles now in conceptual design. However, it is clear that the structural concepts needed to make such next-generation vehicles sufficiently durable and lightweight will involve novel structural arrangements and material systems. During typical operating conditions, aircraft are subjected to random loads due to engine noise and other acoustic vibrations. The random acoustic pressure load, combined with other extreme conditions like elevated temperatures, turbulence, etc., may lead to the failure of the aircraft structure.

The potential for reducing weight from using integrated functional structures is great, though designs that enhance damage tolerance are key to their success. Because of the intensity and complexity of combined loads on future vehicles, unprecedented integration of structural configuration and overall material behavior — at the design stage — is required to meet damage tolerance demands. Cost and flight environment requirements preclude the traditional design-build-test-redesign approach; hence this integration must be done largely through simulation and digital prototyping.. The focus of our research program is precisely this integration by provision of next-generation, validated, computational simulation capabilities for damage evolution and mitigation in structures composed of novel materials under combined loading, especially thermal-mechanical-acoustical (TMA) loads.

The Air Force capabilities desired in the future require the structural integrity of aircraft during their high-performance operations in extreme environments. This unprecedented goal demands new techniques of analysis, design and manufacture, and specially-engineered materials/structures including functionally graded materials (FGM). The intrinsic and epistemic uncertainties in such extreme loads and the structural behaviors of new materials are significant and propagated into the performance of the air vehicle systems. This causes unquantified risks of structural failures during the operations. We are developing a probabilistic framework that will identify/synthesize the uncertainties in the components so that risk-quantified designs of aircraft systems can be achieved. It will also enable design modifications and improvements that minimize the risks within the available budget and constraints.

Modeling/simulation — Used in reliability analysis, design, and for designing effective experiments
Experiments — Data used for parameter identification studies to improve modeling effort and validation of simulations
Risk/reliability — Algorithms used for reliability analysis, parameter identification and design

1.2 Midwest Structural Sciences Center

The Midwest Structural Sciences Center is a collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/VA SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames. The MSSC team is viewed as a “living organization” whose members may change over time to meet the needs of the collaborative partnership.

The team employs analytical, computational, experimental, personnel and financial resources from all three organizations, and will seek additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all three sites and will be applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their colleagues at AFRL/VA SSC to evaluate and extend our understanding of materials and structures in aerospace structural components that experience extreme combined environments.

Collaboration among the partners is frequent (near-daily) and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and AFRL/VA visitor office spaces have been earmarked at UI to directly support the MSSC, as have graduate student tuition waivers from AFIT. These matching funds will approach $1 million over the initial five-year program life.

High-performance hypersonic aircraft are expected to have stringent structural requirements, especially in regard to STATS components. Many of these structural components may include functionally-graded materials (FGM) specifically designed and manufactured to address the combined thermo-mechanical-acoustic loadings unique to hypersonic applications. MSSC research will develop models that account for the damage progression in both the ductile and brittle phases of FGMs. Especially important will be the development of efficient methods for quantifying the uncertain responses and the risks of STATS. Among other techniques, methods to identify important input uncertainties through sensitivity analyses that will allow us to focus on the dominant uncertainties that threaten successful risk-quantified structural design (RQSD) are envisioned. Initial work will focus on a carefully selected, small-scale aircraft substructure — perhaps a wing torque box — that can be fully characterized experimentally. This structure will be employed in assessing new methodologies for predictive science tying together RQSD, high-fidelity simulations, and novel experimental techniques.

MSSC Team Members

University of Illinois

- Bodony — Acoustic response prediction
- Brandyberry — Uncertainty quantification and risk analysis
- Duarte — GFEA, structural analysis, multiscale analysis
- Geubelle — Multiscale analysis, FEA
- Huang — Constitutive modeling, micromechanics
- Lambros — Experiments, high strain rates, FGM
- Paulino — FGM, Multiscale analysis, structural analysis
- Sehitoglu — Thermomechanical response, experiments
- Song — Risk, reliability, stochastic events, FEA
- Tortorelli — Sensitivity, optimization

AFRL/VA SSC

- Acoustic experiments, aeroframe design, operating environments, large-scale structural testing

Existing constitutive materials models are generally phenomenological, i.e., they are based on some empirical formulae (e.g., power law) to be fitted to laboratory tests. The phenomenological models rarely work well for advanced materials subjected to extreme conditions since they do not account for the significant microstructure change under the extreme environment. Thus novel, physically based constitutive models are being developed under the MSSC umbrella.

Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the wide variety of fatigue loadings possible. In parallel to our simulation and RQSD tasks, Center researchers will conduct series of experiments to determine the relative importance of low cycle, high cycle, and fatigue crack growth in materials subjected to thermomechanical and acoustic fatigue. Experiments are being developed to understand the interaction between high stresses associated with the thermal loading, superimposed with low stresses from an acoustic-type loading. Table 1 presents an overview of the nine initial research projects along with a matrix that depicts the interactions among the projects. In each project, UI and VA SSC personnel are teamed to encourage tight relationships between university and government researchers. The following subsections describe the research plan.

2 Technical Project Progress

A — Coupled Thermo-Mechanical-Acoustic Analysis and Simulation of STATS

A1 Design of STATS using Topology Optimization (Paulino, Stump, Byrd)

A2 Adaptive Modeling of Heterogeneous Shells Subjected to Thermomechanical Loads (Duarte, O'Hara, Eason)

A3 Integrated Fluid/Structure Interaction Simulation (Geubelle, Joumaa, Hollkamp)

B — Identification and Definition of Structural Limit States for STATS

B1 Failure Analysis of FG Aircraft Components in Combined Environments (Huang, Xiao, Tuegel)

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Tortorelli, Ostoja-Starzewski, Bellur-Ramiswamy, Eason)

C — Framework and Methodologies for Risk-quantified Structural Assessment of STATS

C1 Uncertainty/Risk Quantification Methods for STATS (Song, Lee, Tuegel)

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Brandyberry, Tuegel)

D — Experimentation, Verification, and Validation

D1 Experimental Investigation of Thermomechanical Fatigue Failure Modes (Sehitoglu, Efstathiou, Hauber)

D2 Development of Novel Experimental Techniques for Validating Coupled Thermomechanical Behavior (Lambros, Carroll, Spottswood)

A — Coupled Thermo-Mechanical-Acoustic Analysis and Simulation of STATS

Three projects are being pursued to address the coupled thermomechanical-acoustic analysis and simulation of STATS. The first, entitled "Design of STATS using Topology Optimization," is led by Glaucio Paulino (UI) and Larry Byrd (AFRL/VA SSC). As noted above, the Air Force expects that the next generation of high-performance hypersonic aircraft will have stringent structural requirements, especially in regard to STATS components. Continuum (as opposed to traditional) topology optimization will be used as a rational means to obtain innovative structural designs, which will improve performance and lower costs. This project will develop a multiscale, 2- and 3-D continuum topology optimization that ac-

Table 1: MSSC Research Project Interactions

	Project Title	A1	A2	A3	B1	B2	C1	C2	D1	D2
A1	Topology Optimization				X				X	
A2	Modeling of Heterogeneous Shells	X								
A3	Integrated FSI Simulations									X
B1	Failure Models for FG Structures	X							X	X
B2	Optimization and Bounds		X		X				X	X
C1	Uncertainty/Risk Quantification					X		X		
C2	Validation with Uncertainties						X			
D1	Thermomechanical Fatigue Experiments				X		X	X		X
D2	Novel Experimental Techniques			X	X	X			X	

counts for material gradient effects. By multiscale we mean that the framework will optimize both the material and component scales. For example, if we consider a functionally graded STATS material, this system will optimize not only topological arrangement at the component scale, but also material property distribution within a candidate arrangement.

The second project in this thematic area is "Adaptive Modeling of Heterogeneous Shells Subjected to Thermomechanical Loads," led by Armando Duarte (UI) and Thomas Eason (AFRL/VA SSC). A computational framework to simulate the behavior of heterogeneous shell structures operating under a broad range of service conditions will be developed. In the first phase of the project (three to four years), we will focus on the case of CMC shells subjected to combined thermomechanical loads. The homogenization will be done with the aid of representative volume elements.

Philippe Geubelle (UI) and Joe Hollkamp (AFRL/VA SSC) will team with others in a project to explore "Integrated Structural/Acoustic Interaction Simulation of STATS." Based on introductory work done in the UI/DOE Center for Simulation of Advanced Rockets (CSAR), the team is developing 2-D and 3-D coupled structural-acoustic codes aimed at capturing the complex interaction of acoustic waves impinging STATS and those associated with the dynamic response of the structure. The unstructured finite element codes to be developed will be based on the *Rocstar* integrated multiphysics code used in CSAR, taking advantage of a unique interface module, *Rocface*, that allows for the very accurate and conservative transfer of loads across non-matching discretized interfaces. Special emphasis will be placed in the accurate capture of the dynamic bending response of the thin-walled structures that tend to be especially prone to acoustic fatigue failure. A major part of the effort will be dedicated to the verification and validation of the individual acoustic and structural components of the integrated code and of the integrated structural-acoustic solver based on theoretical, numerical and experimental data available in the open literature and at AFRL.

A1 Design of STATS using Topology Optimization (Paulino, Stump, Byrd)

The most significant synergistic achievement during the past term was to identify the main features that a topology optimization code must have in order to be applicable to the design of STATS. Besides the features proposed on the project description, such as coupled multiphysics and the capability to solve large scale problems, the necessity to consider radiation boundary conditions and temperature dependent material properties was identified.

In terms of tangible output, a 2-D topology optimization code capable of providing the conceptual design of hot structures was developed. This code is able to find the optimal geometry for the structure underneath the skin of an aircraft component such that the temperature is as uniform as possible over the structure (Figure 1).

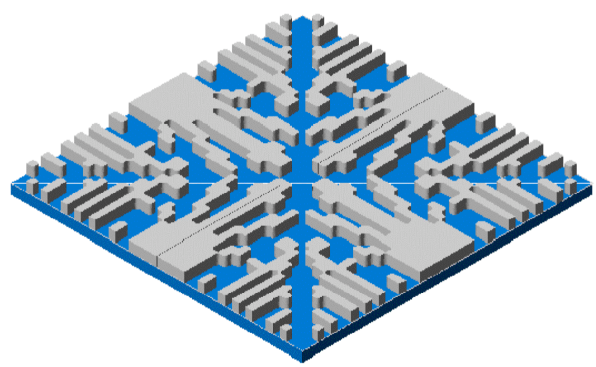


Fig. 1: Example of skeletal structure to be inserted underneath skin of component to better distribute temperature on component.

The development of the 3-D code considering the features proposed and identified has begun, and is currently under vigorous development. The code is based on the framework of the public C/C++ libraries LibMesh, PETSc and the in-house solver MINRES, which utilizes the Krylov subspace recycling method. The code developed in this framework will be robust enough to solve large problems, and flexible enough to incorporate new features for optimal design.

A2 Adaptive Modeling of Heterogeneous Shells Subjected to Thermomechanical Loads (Duarte, O'Hara, Eason)

A finite element solver capable of handling heat transfer problems involving sharp thermal gradients, such as a vehicle in hypersonic flight, has been implemented. The current solver is steady state and assumes a linear, isotropic material. Both constant and non-constant surface fluxes and internal sources can be applied to the domain of interest. Presently, Dirichlet, Neumann, and mixed-type boundary conditions can all be accommodated. While the solver is capable of utilizing Generalized Finite Element Method techniques, traditional FEM techniques were first explored to investigate the potential capability of existing methodologies to efficiently solve problems with sharp thermal gradients (Figure 2). Convergence analyses were performed for the error in the energy norm for low order elements, which have proven capable of controlling the global error in the energy norm, but they do so inefficiently requiring very large numbers of degrees of freedom. The large problem size arises from the need for high levels of local refinement in the rough region surrounding the peak value in the temperature field (Figure 3). Uniform refinement is also possible, but this refinement strategy makes the problem size unnecessarily large. An hp-adaptive finite element analysis was then performed on the same model problem. The higher order elements proved effective in controlling both the error in the energy norm, as well as the local error in the maximum temperature. Again, large levels of local refinement are required to capture the behavior, but the higher order elements are capable of controlling both error values, and doing so more efficiently than the lower order, standard finite elements.

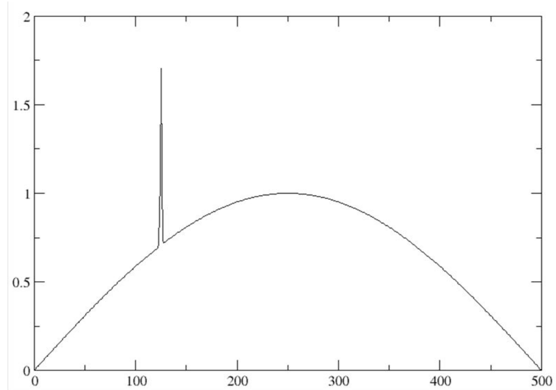


Fig. 2: Temperature field for model problem with large thermal gradient

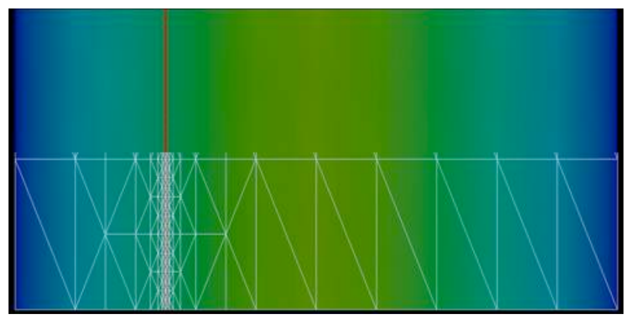


Fig. 3: Sample output of temperature field with high level of local refinement.

A3 Integrated Fluid/Structure Interaction Simulation (Bodony, Geubelle, Joumaa, Hollkamp)

Over the past few months, our efforts have been dedicated to the development, implementation and verification of a boundary element solver able to simulate a wide range of 2-D acoustic problems involving static and moving boundaries. This particular numerical method was adopted for its ability to capture very efficiently the response of an infinite linear acoustic medium, as the infinite nature of the domain is naturally included in the Green's function that defines the boundary integral formulation. An example of the verification study, shown in Figure 4, involves the reflection of a pulse off a non-moving rigid plate. Once the acoustic solver is fully verified and its stability and accuracy characteristics assessed, it will be coupled with the linear and nonlinear structural finite element solver also developed and verified over the past few months. In its first implementation, the coupled structural/acoustic solver will rely on matching spatial and temporal discretizations. Then, recent advances in the modeling of multiphysics problems will be introduced, allowing for non-matching spatial and temporal discretizations between the acoustic and structural domains. The ultimate goal is to use the coupled solver to investigate the dynamics of thin-walled structures in the presence of high acoustic loads.

B — Identification and Definition of Structural Limit States for STATS

Two projects have been crafted to assess the structural limit states for STATS. Yonggang (Young) Huang (UI) and Eric Tuegel (AFRL/VA SSC) will join to develop a scalable cohesive failure model for functionally graded materials and structures based on the experimentally identified mechanisms. Such a model can be used to predict the crack nucleation, initiation and progressive growth in various material systems. These investigators will collaborate directly with experimentalists to link the microstructures to the macroscopic failure mechanisms, and determine the actual cohesive failure model parameters.

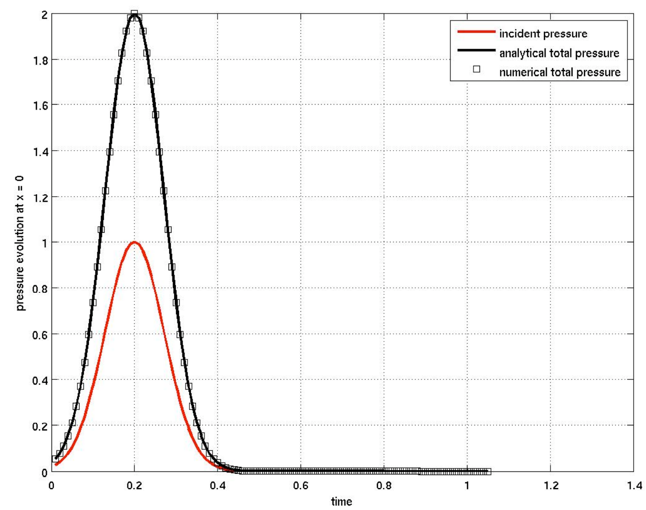


Fig. 4: Verification of acoustic boundary element solver: reflection of incident pulse (red curve) off rigid planar surface.

A second project in this theme area will establish a methodology that identifies the optimum spatial constituent distribution to achieve the desired performance for STATS. Daniel Tortorelli (UI), Thomas Eason (AFRL/VA SSC) and their colleagues will investigate the behavior of randomly structured materials using lattice models to obtain computationally efficient bounds on constitutive response enabling structural scale optimization of STATS. The initial phase of this project is to develop methodology using the lattice model that can generate the random microstructures present in STATS and perform thermoelastic finite element mesoscale analyses to obtain bounds on elastic and thermal properties. Research into spatial morphology representations and automated finite element meshing will be required to complete this research task.

B1 Failure Analysis of FG Aircraft Components in Combined Environments (Huang, Xiao, Tuegel)

We have established the cohesive law for fiber/matrix interfaces in composites that are characterized by the van der Waals force. The tensile cohesive strength and cohesive energy are given in terms of the densities of reinforcements and matrix, as well as the parameters in the van der Waals force. The simple, analytical expressions of the cohesive law are obtained, which are useful to study the effect of interfaces on the macroscopic behavior of the composites. The effect of matrix surface roughness on the cohesive law is also studied.

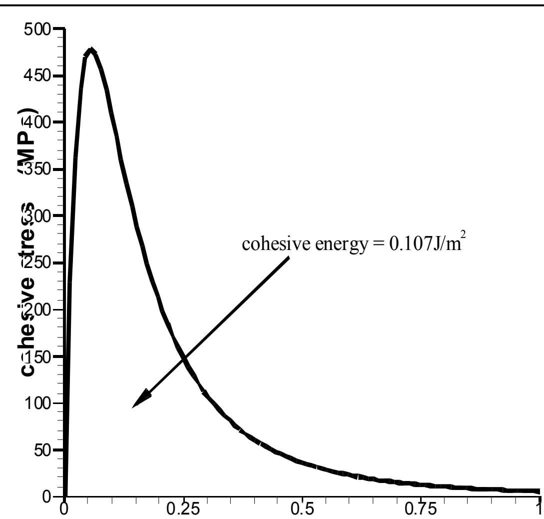


Fig. 5: Cohesive law for fiber/matrix interface in composite characterized by van der Waals interaction

Such cohesive law has been implemented in the finite element program to study the fracture initiation and crack growth in composites (Figure 5). It is shown that without any externally imposed fracture criterion the cohesive law simulations capture the defect initiation and crack propagation in composites upon mechanical loading. For example, it has captured crack

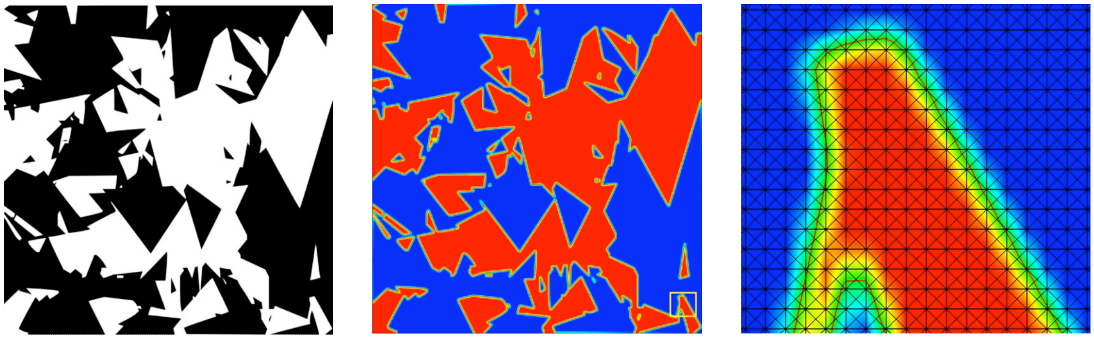


Figure 6: (Left) Computer generated microstructure of RVE; (middle) Corresponding level set data; (right) Zoom of inset box in lower right corner of middle figure.

kinking and propagation upon shear-dominated loading, as well as mixed-mode loading.

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Tortorelli, Ostoja-Starzewski, Bellur-Ramiswamy, Eason)

The randomness of the microstructure in FGMs brings a statistical nature to their material properties that must be considered when performing structural reliability analyses and/or stochastic finite element analyses. Hence the characterization of randomness in the FGM properties becomes an important aspect in the design of STATS. We propose the following numerical procedure towards this end:

- Use the image analysis capabilities of the *Micromorph* software on experimentally obtained micrographs to obtain statistics on the microstructure morphology, e.g. volume fraction, average particle size, particle spacing etc.
- Use *Micromorph* to generate microstructures with similar statistics
- Use the Generalized FEM program to analyze each realization as part of a Monte Carlo study to obtain bounds and statistics on "effective" properties
- Verify the bounds with experiments (this may not be done for this 2-D study, but for our future 3-D study)

Our work to date addresses the second and third items above. We numerically generate microstructure binary images (Figure 6(a)) for random samples based on a given morphology with known statistics. Next, we use our newly developed computer code to embed the sample onto a structured finite element mesh. This is done by converting the binary image into a level set (Figure 6(b)). Finally we use our 2-D Generalized FEM code to evaluate the apparent material properties of the sample.

C — Framework and Methodologies for Risk-quantified Structural Assessment of STATS

The application of STATS in next generation airframes will largely depend upon confidence enabled through risk-quantified structural assessment. Two MSSC projects address this area. Junho Song (UI) and Eric Tuegel (AFRL/VA SSC) lead a project to develop novel "Uncertainty/Risk Quantification Methods for STATS." This project develops efficient methods for quantifying the uncertain responses and the risks through computational simulations. Also developed are the methods to identify important input uncertainties through sensitivity analyses, which will allow a focus on the dominant uncertainties during the risk-quantified structural design (RQSD). AFRL/VA SSC will provide a small-scale example of aircraft substructure such as a wing torque box to use as an example throughout the development of uncertainty/risk quantification methods.

The second project in this theme focuses on "Validation with Uncertainties in Both Simulation and Experimental Results." Led by Mark Brandyberry (UI) and Eric Tuegel (AFRL/VA SSC), this research team will provide accurate simulation tools with which to make predictive calculations of physical processes of interest. Simulations are, by their nature, approximations to reality, and as such have various uncertainties associated with their results. Often it is difficult to adequately assess these uncertainties due to the computational time required to make the runs, and thus it is desired to minimize the number of simulations required. This effort seeks to understand the relationship between input uncertainties and simulation confidence when constrained by a limited number of computational runs.

C1 Uncertainty/Risk Quantification Methods for STATS (Song, Lee, Tuegel)

This project aims to develop efficient methods for quantifying the uncertain responses and the risks of spatially tailored aero-thermal structures (STATS) by computational simulations. Also developed are methods to systematically identify important input uncertainties, which will enable us to focus on the dominant uncertainties during risk-quantified design of aircraft structures (Figure 7). Because aircraft are complex structural systems consisting of many structural components, the project also aims to develop efficient reliability analysis methods to estimate such system risks and to identify important components and input uncertainties in terms of the likelihood of system failures.

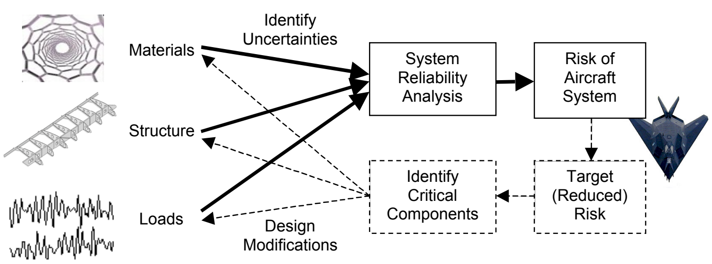
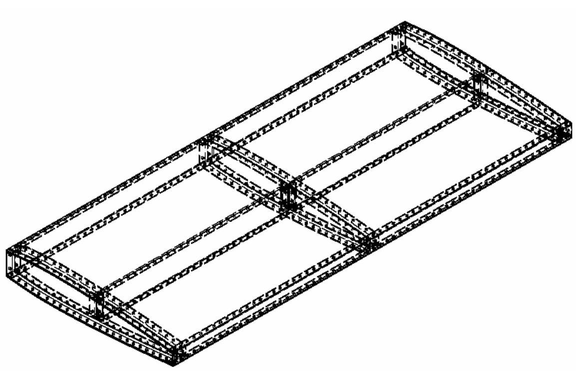


Fig. 7: Probabilistic framework for risk-quantified design of aircraft

A numerical example of an aircraft structure system is being developed as a testbed for various reliability methods that will be used or developed by this project. Figure 8 shows the configuration of the selected wing torque box system and one of the detailed design drawings developed for this project by the AFRL. Based on this design, we are currently building a finite element (FE) model for computational simulations by a general FE code, ABAQUS.

Concurrently, we have been building a computer code to perform FE-reliability analyses of STATS. This is being developed by linking ABAQUS with a Matlab-based, open-source reliability analysis code called FERUM. This project will use the developed code, FERUM-ABAQUS in order to test existing component/system reliability methods and new methods developed in the future. When the FE model for the wing torque box is completed, a series of reliability analyses will be performed using FERUM-ABAQUS to identify unique challenges in estimating the uncertain responses and the component/system risks of STATS.



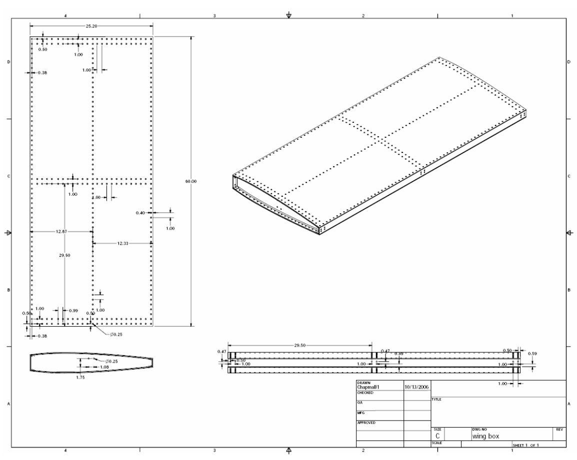


Fig. 8: Generic wing torque box

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Brandyberry, Tuegel)

Over the past year, progress has been made in the areas of 1) sample-based surrogate-model clustered uncertainty propagation through complex engineering models, 2) methods for statistical comparison of continuous uncertain simulation results with uncertain experimental results, and 3) consideration of new methods for defining the validation of multi-dimensional continuous field simulations with point-value, time-series experimental data. Exploration of techniques for producing the simulation result uncertainty estimates provided useful UQ formats to work with. Time-series comparisons of simulation UQ results against spatially limited experimental data were explored by using simple hypothesis testing comparisons at multiple times. This yielded results for mean value comparisons between simulation and experimental distributions that provided statistical evidence of similarity between the two, and by inference, validation of the simulations. Recent work has involved extending the ideas of single-point comparisons to simultaneous multiple point comparisons, with multiple comparison criteria, through the use of multi-attribute decision analysis. The goal is to consider the simulation versus experimental distribution match at multiple points on a structure under simulation/design, while also considering multiple system response quantities (SRQs) such as strains, deflections, cracking, etc. To enable validation of a computer simulation as a design tool, it is not sufficient to consider only a single response quantity at a single point and then consider the simulation validated. Different comparisons may have different importance (i.e., different utilities in the decision analysis). Figure 9 shows a typical decision tree depiction of a decision process applied to a structure at two points, and considering strain comparisons at both points as well as crack prediction at both points. The strain comparisons are modeled as continuous distribution mean comparisons with Utilities of either comparing well (in a mean sense) or not, while cracking is modeled as a binomial yes/no process, with different utilities depending on whether the simulation and experiment both predict cracking, and differing utilities at the two measured points as well. The latter reflects the possibility that cracks at one spatial point may be critical, while at another point may not be.

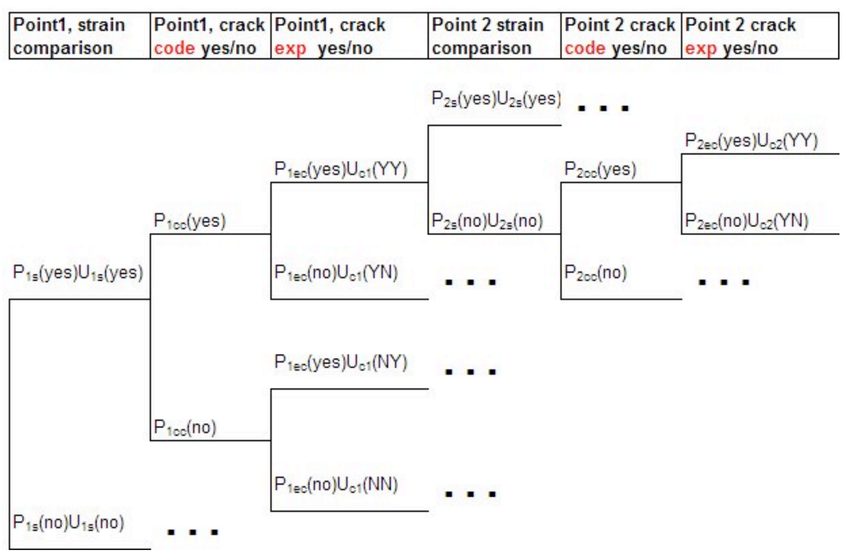


Fig. 9: Typical decision tree showing split probabilities (P()) and utility functions ($U_{ci}()$)

D — Experimentation, Verification, and Validation

Two critical projects enable the completed circle of "design—simulation—implementation." An "Experimental Investigation of Thermomechanical Fatigue Failure Modes of Aerospace Structures" will be led by Huseyin Sehitoglu (UI) and Brett Hauber (AFRL/VA SSC). Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the very wide variety of fatigue loadings possible. In this project we will conduct a series of experiments to determine the relative importance of low cycle, high cycle and fatigue crack growth in a metal matrix composite subjected to thermomechanical fatigue. Since crack nucleation and growth is a continuous process, experiments will also be conducted to observe the crack growth phenomenon.

John Lambros (UI) and Michael Spottswood (AFRL/VA SSC) will team with their colleagues in the "Development of Novel Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework." A three-phase experimental program is planned to explore the role of combined thermomechanical fatigue. They will develop novel diagnostics such as high temperature digital image correlation and high temperature fiber optic strain gauges that will allow detailed full-field and real-time interrogation of events such as damage accumulation, and crack nucleation and growth in fatigue.

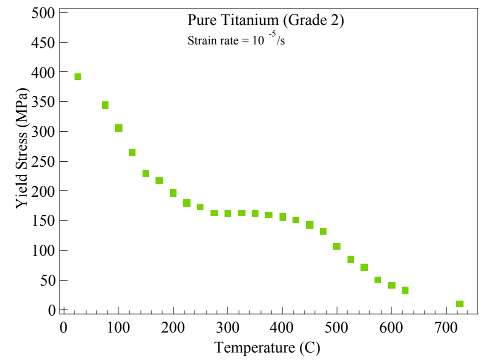


Fig. 10: Temperature dependence of tensile yield strength

D1 Experimental Investigation of Thermomechanical Fatigue Failure Modes (Sehitoglu, Efstathiou, Hauber)

An experimental apparatus and control software was developed for combined thermal and mechanical fatigue experimentation. This apparatus incorporates digital image correlation (DIC) to generate full field information. Initial experimentation was used to develop titanium's temperature dependence of Young's modulus, coefficient of thermal expansion and, yield strength shown in Figure 10. Agreement between extensometer measured strain and DIC measured strain was found for uniform deformation; this is shown in Figure 11 for strains below five percent. Subsequent experimentation was focused on resolving full field phenomena such as the localized deformation in front of cracks and interfaces.

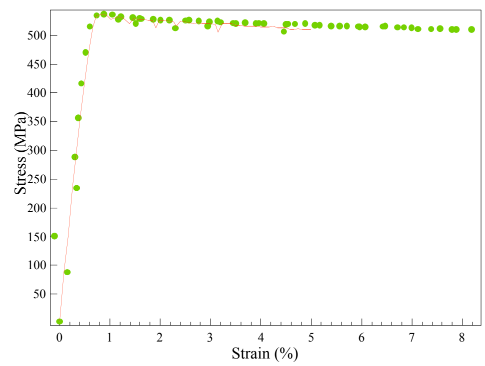


Fig. 11: Stress-strain curve measured by extensometer (red) and DIC (green)

As we are awaiting the arrival of titanium based monolithic and graded materials, we have conducted experiments on materials with multiphase microstructures. The multiphase materials are model materials for future experiments since they display localized deformation or damage during loading which we expect to find in FGMs. Figure 12 shows a typical strain field obtained using the DIC technique. The features identified by different colors accurately represent the interfacial features in the corresponding image. Also, the strain measured in these regions agrees with theoretical calculations. Experiments at different magnifications permitted for macroscopic and microscopic features to be resolved. This technique successfully measured the localized deformation and its evolution during the loading history. Although the strain field shown in Figure 12 is not for a FGM, we expect to encounter similar abrupt strain transitions at interfaces between ceramic and me-

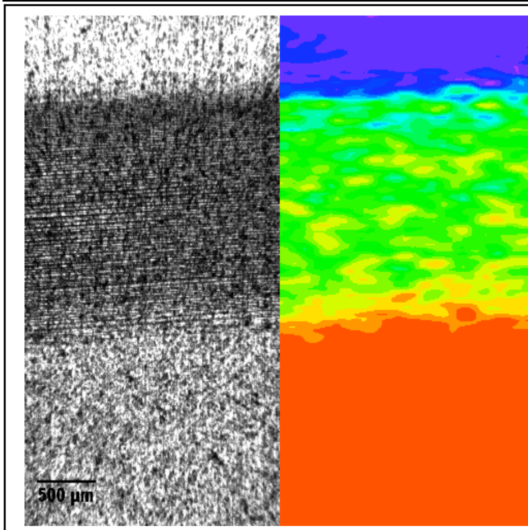


Fig. 12: Full-field strains resolved using DIC technique showing multiple interfaces and corresponding image

tallic constituents. Full-field measurements such as those shown in Figure 3 are essential for validating models developed by other teams in this program.

D2 Development of Novel Experimental Techniques for Validating Coupled Thermomechanical Behavior (Lambros, Carroll, Spottswood)

First, a testing system was setup that combined mechanical and thermal loading devices and sensors, a vision system, and software. Baseline tests were then performed to ensure the system was working properly and to ensure that results obtained using digital image correlation (DIC) were consistent with other methods of measurement. This included several rigid translation, rigid rotation, high temperature, simple tension, and several combinations of these four tests. An example of typical results obtained using DIC are shown in Figure 13 for a simple tension specimen.

Next, tests were performed on grade 2 titanium including the determination of the elastic modulus, yield strength, and coefficient of thermal expansion using digital image correlation. Determination of these properties will be needed for each material component used in a functionally graded material (FGM) so that the models developed in this program can accurately characterize FGMs. Shown in Figure 14 is a plot of how the coefficient of thermal expansion varies with temperature. Plots like Figure 14 will be needed for each material in the FGM for several properties.

Digital image correlation was also used to observe displacement fields around crack tips. Stress intensity factors were determined from these displacement fields; the ability to determine stress intensity factors will be necessary to characterize fatigue in the crack-growth regime.

3 Management

An Executive Director (William Dick) manages the Center and two co-Technical Directors (Glaucio Paulino and Daniel Tortorelli) work with their research counterparts at AFRL/VA SSC. A Science Steering Committee of program participants (UI and AFRL/VA SSC) convenes weekly to guide the directors in program execution. Collaboration among the partners has been frequent (near-daily) and intense (co-advised research projects and graduate theses, teamed simulation and experiments, anticipating co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and visitor office spaces exist at UI to directly support the MSSC. The Directors and Science Steering Committee members are responsible for nurturing the research program, administering the Center, and maintaining and expanding relationships with AFRL/VA SSC. This directorate provides the leadership necessary to ensure that the Center identifies the most important research areas, attracts the most qualified researchers, and pursues and completes the work effectively over the long term. A small administrative staff works to execute Center activities.

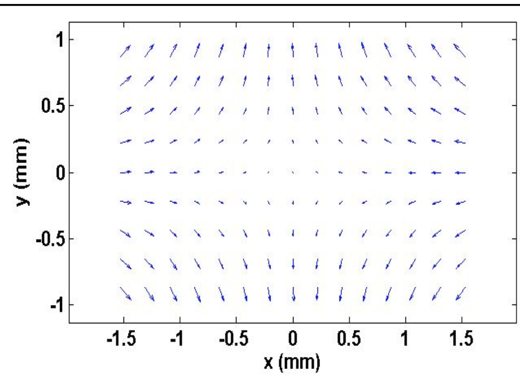


Fig. 13: Displacement field for simple tension

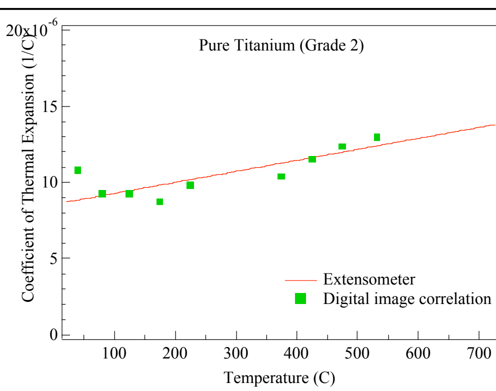


Fig. 14: Coefficient of thermal expansion of test with rigid body motion subtracted (scale=100)

The MSSC is housed within the UI Computational Science and Engineering (CSE) Program. CSE is inherently interdisciplinary, drawing faculty, staff and students from 14 departments and requiring expertise in advanced computing technology, as well as in one or more applied disciplines. The purpose of the academic CSE Degree Option is a perfect complement to the goals of the AFRL/VA SSC program — to foster interdisciplinary, computationally oriented structural sciences research among all fields of science and engineering, and to prepare students to work effectively in such environments. This academic structure lends itself naturally to the requirements of the MSSC: a free flow of students and ideas across academic departmental, college, and governmental unit lines. A far-reaching Visitors Program is being implemented to encourage close collaboration among the team members. Research offices and computational facilities in CSE space are available for this purpose.

4 Publications

Bellur Ramaswamy, R., E. Fried, X. Jiao, and D. A. Tortorelli, "Simulating Solid-Solid Phase Transition in Shape-Memory Alloy Microstructure by Face-Offsetting Method.," presented at Multiscale and Functionally Graded Materials Conference, Oct. 15-18, 2006, Hawaii.

Dick, William A., "Midwest Structural Sciences Center — A University-Government Partnership," Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, October 2006.

Duarte, C. A., L. G. Reno, A. Simone, and E. van der Giessen. "Hp generalized finite elements for three-dimensional branched cracks and polycrystals," In G. H. Paulino, M.-J. Pindera, R. H. Dodds, and F. A. Rochinha, editors, Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, 15-18 October 2006. Keynote Lecture.

Hauber, B.; Brockman, R. and Paulino, G. H. "On Fatigue Crack Propagation in FGMs: Experiments and Simulations" presented at "Multiscale and Functionally Graded Materials Conference" M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Nguyen, T.; Song, J. and Paulino, G. H. "Probabilistic Fracture Analysis of Functional Graded Materials - II: Implementation and Numerical Results" presented at "Multiscale and Functionally Graded Materials Conference" M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

O'Hara, P., "Finite element analysis of three-dimensional heat transfer for problems involving sharp thermal gradients," M.Sc. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, 2007.

Song, J.; Nguyen, T. and Paulino, G. H. "Probabilistic Fracture Analysis of Functional Graded Materials - I: Concept and Formulation" presented at "Multiscale and Functionally Graded Materials Conference" M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Stump, F. V.; Silva, E. C. N. and Paulino, G.H. "Topology Optimization with Stress Constraints: Reduction of Stress Concentration in Functionally Graded Structures" presented at "Multiscale and Functionally Graded Materials Conference" M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.